Prospects of Higgs Physics at the LHC ⋆

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Summary. The search for the Higgs boson is a major physics goal of the future Large Hadron Collider. The discovery potential is described as a function of the Higgs mass. It is shown that a Standard Model Higgs boson can be discovered within the first year of data taking. The status of MSSM Higgs searches is also discussed.

1 Introduction

A major physics priority of the experiments at the future proton-proton Large Hadron Collider (LHC) at CERN will be the search for the Higgs boson, a cornerstone for the study of the nature of electroweak symmetry breaking. Two general purpose experiments under construction, CMS [1] and ATLAS [2], have been optimized to cover a large spectrum of possible physics signatures within the data taking environment of the LHC.

Detailed simulations of both experiments have been performed to demonstrate the feasibility of the discovery of the Standard Model (SM) Higgs in a broad range of the SM Higgs masses. The LHC experiments have also a large potential to explore the Minimal Supersymmetric Standard Model (MSSM) Higgs sector.

2 Running Conditions and Physics Analysis

Physics studies in CMS and ATLAS assume an initial instantaneous luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (low luminosity regime) for the turn on of the LHC. The instantaneous luminosity is expected to increase gradually before reaching the designed value of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (high luminosity regime). A total integrated luminosity of 10 fb^{-1} should be delivered during the first year of data taking. After the following year 30 fb^{-1} will be delivered. Once the design luminosity is reached 100 fb^{-1} will be available per year.

A number of elements are specific to the physics performance studies reported here:

- The non diffractive $p-p$ inelastic cross section is assumed to be 70 mb. It is expected that an average of ≈ 2 and ≈ 20 inelastic collisions will occur together with the hard interaction for low and high luminosity regimes, respectively [1]. This effect are included for both the low and high luminosity regimes.

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[1] This effect is usually referred to as pile-up.

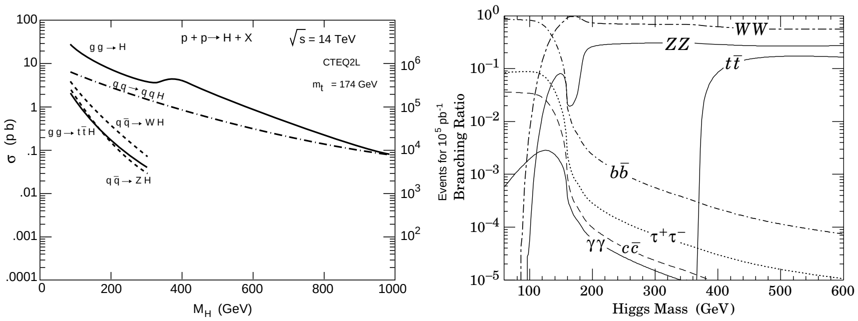

Fig. 1. Higgs production cross section at the LHC and Higgs branching ratios as a function of the Higgs mass, M_H.

- Born-level cross-sections for both signal and backgrounds are used. This is motivated by the fact that the higher order QCD corrections (K-factors) to the Born-level cross-sections of a number of meaningful processes are still unknown.
- Parton level MC generators are interfaced with the PYTHIA package [3] for the simulation of partonic showers, hadronization and particle decays.
- In many studies fast simulations of the response of the detectors is used. Nevertheless, the fast simulations are based on a full GEANT simulation of the detectors.

3 The search for the SM Higgs boson

The SM Higgs boson will be produced at the LHC predominantly via gluon-gluon fusion. This is illustrated in the left plot of Fig. 1, in which the expected Born-level cross-sections for each individual mechanisms are plotted as a function of the Higgs mass, M_H [4]. For $M_H > 100\,\mathrm{GeV}$ the second dominant production process goes via the vector boson fusion (VBF). The associated production of SM Higgs with other heavy particles such as W, Z or $t\bar{t}$ pair is sizable for $M_H \leq 200\,\mathrm{GeV}$. The right plot of Fig. 1 displays the SM Higgs branching ratios as a function of M_H [4].

Most of the relevant discovery modes are well assessed [1,2]. The overall sensitivity for the discovery of a SM Higgs boson over the a large mass range $80 < M_H < 1000\,\mathrm{GeV}$ is shown in the left plot of Fig. 2 for one single experiment (ATLAS) and 30 fb^{-1} of accumulated luminosity. The combined sensitivity for both CMS and ATLAS is shown in the right plot of Fig. 2 for 10 fb^{-1}, 30 fb^{-1} and 100 fb^{-1}. The range of M_H close to the LEP limit [5] remains a challenging one.

The strategy adopted for the SM Higgs searches depends upon M_H [1,2]:

- The low mass region, $M_H < 130\,\mathrm{GeV}$. Excellent energy resolution and background rejection are required. Two decays modes are important in this M_H region: $H \to b\bar{b}$ and $H \to \gamma\gamma$. The branching ratio of $H \to b\bar{b}$ is close to 1. However, due to the overwhelming QCD background the signal-to-background ratio for the inclusive production is smaller than 10^{-5}. The $H \to b\bar{b}$ decay mode may be used in the associated production of Higgs with W, Z, or $t\bar{t}$ pair by requiring in the final state a charged lepton (e, μ). The $H \to \gamma\gamma$ channel has a small branching ratio ($\propto 10^{-3}$) but the expected signal-to-background ratio ($\approx 10^{-2}$) makes this channel interesting for inclusive searches.

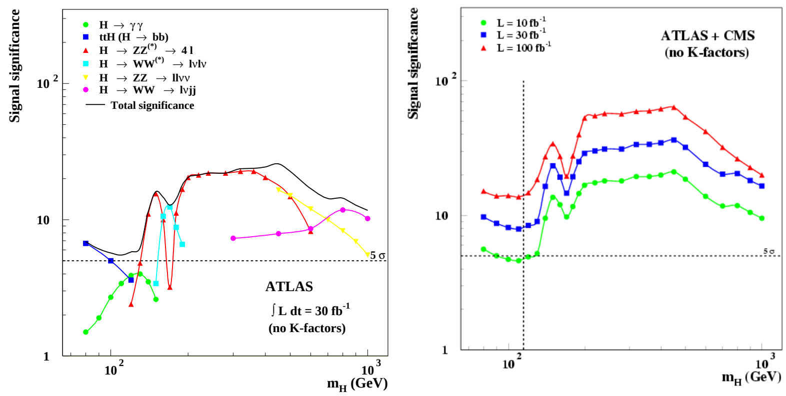

Fig. 2. Sensitivity for the discovery of a SM Higgs boson as a function of M_H. The statistical significances are plotted for individual channels, assuming an integrated luminosity of 30 fb^{-1} (left) for the ATLAS experiment. The overall statistical significance is plotted (right) as a function of the Higgs mass for 10, 30, and 100 fb^{-1} for CMS and ATLAS combined.

- The intermediate mass region, $130\,\mathrm{GeV} < M_H < 2M_Z$. The most powerful channels are $H \to ZZ^{(*)} \to 4l$ and $H \to WW^{(*)} \to l\nu l\nu$. The latter can be used in inclusive and associated W production.
- The High mass region, $M_H > M_Z$. Here the discovery is most straightforward thanks to the $H \to ZZ \to 4l$ channels. In this case, a narrow resonance is expected in the presence of little background. For very heavy masses ($M_H >$ 500 GeV) the production cross-section decreases noticeably. To compensate this the decay modes $H \to ZZ \to ll\nu\nu$ and $H \to WW \to l\nu\ 2jets$ are used.

3.1 Recent Progress in SM Higgs Searches

In earlier physics performance studies the searches for the SM Higgs with two forward jets [2] was considered for $M_H > 300\,\mathrm{GeV}$ [2]. The bulk of the recent progress in performance studies for SM Higgs searches is related to the inclusion of VBF modes in the low M_H region [6,7,8,9,10].

Analyses performed at the parton level with $H \to WW^*$ and $H \to \tau\tau$ suggested that the VBF modes could be the most powerful discovery modes in the range $115 < M_H < 200\,\mathrm{GeV}$ [11,12,13]. The analyses for the WW^* and $\tau\tau$ Higgs decay modes have been redone. A more detailed simulation of the LHC detectors has been implemented. This includes the forward jet tagging and the central jet veto efficiencies. The physics performance had been assessed for the low luminosity regime and for integrated luminosity values of up to 30 fb^{-1}.

The basic signature of this process with WW^* and $\tau\tau$ Higgs decay modes is:

- Two energetic jets in the forward detectors (tagging jets).
- Suppressed hadronic activity between tagging jets.

[2] This enhances the relative contribution from the VBF mechanism.

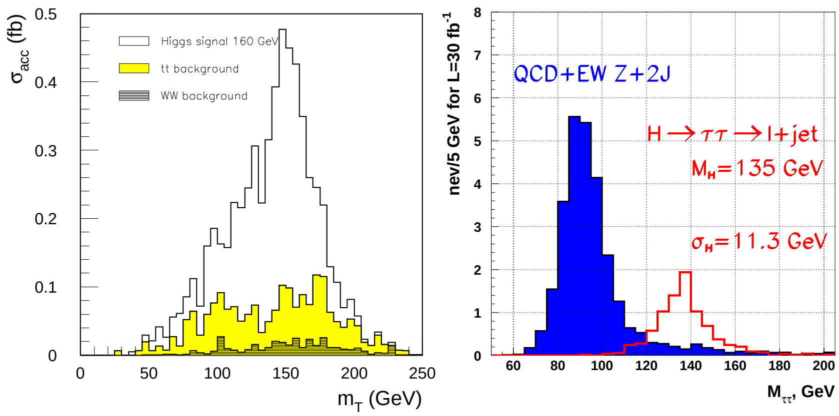

Fig. 3. The left plot shows the expected M_T distribution for $M_H = 160\,\mathrm{GeV}$ with $H \to WW^{(*)} \to l^+l^-\not{p}_T$. The accepted cross-sections $d\sigma/dM_T$ (in fb/5 GeV) are shown. The yellow and black histograms correspond to the contribution from the $t\bar{t}$ and WW backgrounds, respectively. The right plot shows the distribution of the invariant mass of the *tau*-pair for $M_H = 135\,\mathrm{GeV}$ with $H \to \tau\tau \to l + jet$ (in events/5 GeV) for an accumulated luminosity of 30 fb^{-1}. The blue and red histograms correspond to the contribution from the major backgrounds (see text) and the signal, respectively.

Because of trigger rate requirements decay modes are chosen with one or two large transverse momentum electrons or muons. The following background processes common to all modes have been considered:

- Production of $t\bar{t}$: At leading order this process contributes as a background due to the two b-jets. Parton emission plays an important role here.
- QCD WW production: The continuum production of W pairs associated with two jets identified as tagging jets.
- Electroweak (EW) WW production: Production of W pairs via de t-channel vector boson exchange associate with jets. The cross-section of this process is small but rejection is harder due to similarities of the final state topologies with the signal processes.
- QCD Drell-Yan associated with jets with $Z/\gamma^\star \to l^+l^-$.
- EW $\tau\tau$ production associated with jets.

The EW WW and $\tau\tau$ backgrounds have been generated with dedicated programs [14]. The Drell-Yan background has been generated using the matrix element calculations for $q \to Zg$ and $qg \to Zg$ provided by the PYTHIA package.

In the $H \to WW^*$ analysis a large rejection may be achieved against the $t\bar{t}$ and the WW backgrounds by taking advantage of the anti-correlation of the spins of the W's of the decay of the Higgs [15]. In this case no mass peak is seen. Instead an excess of events in the transverse mass, M_T, is observed [11,13]. The left plot in Fig. 3 displays the expected M_T distribution for a Higgs of $M_H = 160\,\mathrm{GeV}$ with $H \to WW^{(*)} \to l^+l^-\not{p}_T$. The accepted cross-sections $d\sigma/dM_T$ (in fb/5 GeV) including all efficiency and acceptance factors are shown. The yellow and black histograms

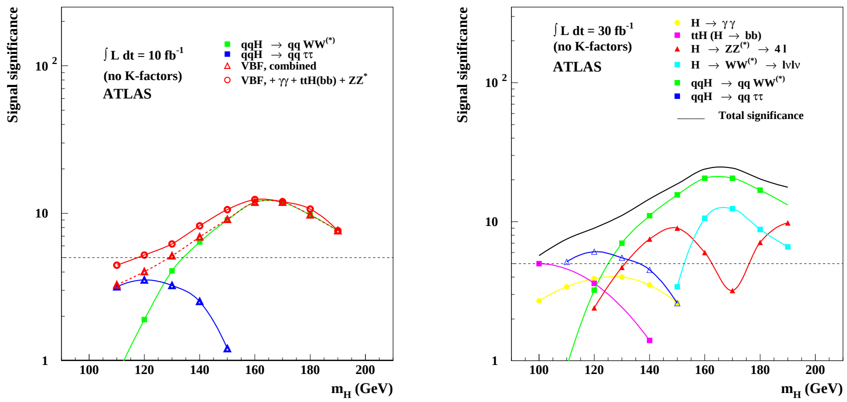

Fig. 4. Impact at low M_H of VBF channels on the sensitivity of a single experiment. The left and right plots show the signal significance for one experiment alone (ATLAS) for 10 fb^{-1} and 30 fb^{-1} of accumulated luminosity, respectively.

correspond to the contribution from the $t\bar{t}$ and WW backgrounds, respectively. In the $H \to \tau\tau$ analysis the invariant mass of the $\tau\tau$, $M_{\tau\tau}$, is reconstructed using the collinear approximation [16]. A resolution of $\approx 10\,\mathrm{GeV}$ is achieved for low mass Higgs. The right plot in Fig. 3 shows the distribution of $M_{\tau\tau}$ for $M_H = 135\,\mathrm{GeV}$ with $H \to \tau\tau \to l + jet$. The number of expected events in bins of 5 GeV for an accumulated luminosity of 30 fb^{-1} is shown. The blue and red histograms correspond to the contribution from the QCD and EW Z associated with two or more jets and the signal, respectively.

Fig. 4 illustrates the impact of VBF channels on the sensitivity of a single experiment to low M_H. The left and right plots show the signal significance for one experiment alone (ATLAS) for 10 fb^{-1} and 30 fb^{-1} of accumulated luminosity, respectively. A 5σ signal significance may be reached for a single experiment with VBF channels combined for $130 < M_H < 190\,\mathrm{GeV}$. When combined with other relevant modes a single experiment can reach a signal significance well above 5σ in the entire range of the Higgs search for 30 fb^{-1} of accumulated luminosity.

4 Recent Progress in MSSM Higgs Searches

With standard assumptions the $M_A/\tan\beta$ plane should be covered by the LHC experiments with the possibility of observing more than one MSSM Higgs in a large portion of the plane [1,2]. Significant progress has been reported on the study of modes specific to the MSSM Higgs sector, namely, $A/H \to \tau\tau$ with two $\tau-$jets in the final state [6]. The left plot in Fig. 5 shows the reconstructed invariant mass of the $\tau\tau$ for $b\bar{b}, H \to \tau\tau \to 2\tau-$jets for $M_H = 500\,\mathrm{GeV}$ and $\tan\beta = 20$ with full detector simulation. The resolution of the reconstructed Higgs is $\approx 15\%$ in the mass range under study. In the case of charged Higgs no mass peak is reconstructed. Instead an excess of events in the M_T distribution is expected. The plot on the right in Fig. 5 displays the reconstructed M_T with $gb \to tH^+, t \to jjb, H^+ \to \tau\nu$

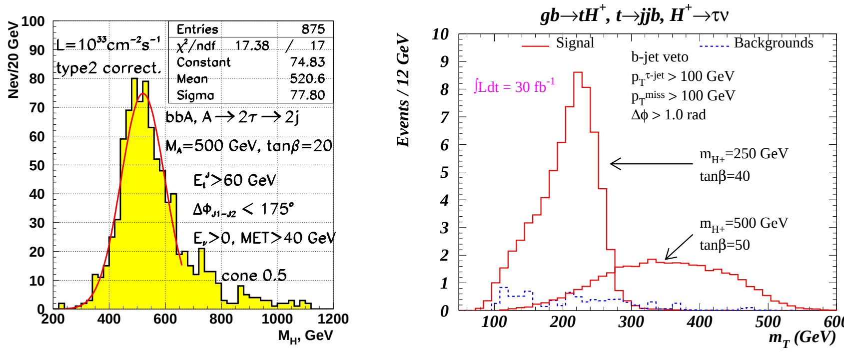

Fig. 5. The left plot shows the reconstructed invariant mass of the $\tau\tau$ (events/20 GeV) for $b\bar{b}, H \to \tau\tau \to 2\tau$jets for $M_H = 500\,\mathrm{GeV}$ and $\tan\beta = 20$. The plot on the right displays the expected M_T (events/12 GeV) with $gb \to tH^+, t \to jjb, H^+ \to \tau\nu$ for $M_{H+} = 250, 500\,\mathrm{GeV}$. The dashed line corresponds to the background contribution. Both plots correspond to 30 fb^{-1} of accumulated luminosity.

for $M_{H+} = 250, 500\,\mathrm{GeV}$. The contribution from SM backgrounds may be heavily suppressed by taking advantage of the polarization of the decaying τ's.

The plot on the left in Fig. 6 shows the expected 5σ contours in the $M_A/\tan\beta$ plane for the MSSM Higgs for one experiment (CMS) in the minimal mixing scenario for 30 fb^{-1} of accumulated luminosity. The improvement in the coverage is mainly due to the inclusion of modes with two $\tau-$jets in the final state. The plot on the right in Fig. 6 corresponds to the 5σ contours for CMS and ATLAS combined for 10 fb^{-1} of accumulated luminosity. The line marked with *SM like h* includes the combination of the SM model like channels, including VBF. This illustrates that most of the MSSM plane will be covered by the two LHC experiments with just 10 fb^{-1} of accumulated luminosity.

Because the suppression of the MSSM Higgs coupling to weak bosons the region of low and medium $\tan\beta$ remains a difficult one for heavy Higgs. Scenarios in which the scale of supersymmetry (SUSY) is low enough so as to allow Higgs decay into SUSY particles or Higgs production from SUSY particle cascades are under investigation. This enhances the sensitivity of the LHC experiments to the low and medium $\tan\beta$ region.

5 Conclusions

The status of performance studies for SM and MSSM Higgs bosons searches at the LHC is discussed. The inclusion of VBF modes in the search for SM Higgs improves the expected signal significance for low and medium M_H. One single experiment may achieve a 5σ signal significance for the range $115 < M_H \lesssim 1000\,\mathrm{GeV}$ with just 10 fb^{-1} of accumulated luminosity.

The coverage of the MSSM plane with more than one Higgs has been significantly enhanced by including heavy Higgs decays into τ's with $\tau-$jets in the final state. Most of the MSSM plane will be covered by the two LHC experiments with just 10 fb^{-1} of accumulated luminosity. Studies have been performed to determine

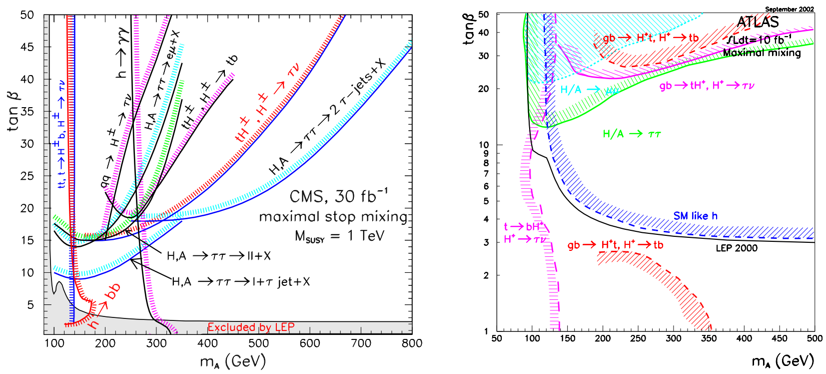

Fig. 6. The plot on the left shows the expected the 5σ contours in the $M_A/\tan\beta$ plane for the MSSM Higgs with CMS for 30 fb^{-1} of accumulated luminosity. The shaded area is excluded by LEP [17]. On the right the 5σ contours for CMS and ATLAS combined for 10 fb^{-1} of accumulated luminosity are shown (see text).

the impact of the inclusion of Higgs decays into SUSY particles and Higgs from SUSY cascades to cover the intermediate and low $\tan\beta$ range.

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